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Development of the community turbulence model at NCAR and its use for studying fundamental turbulence, convection, and stratified shear flow is discussed.

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GEOPHYSICAL TURBULENCE RESEARCH AT NCAR

FINAL REPORT

Robert M. Kerr

2 May 1990

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Boulder, Colorado 80307

1. INTRODUCTION

The Geophysical Turbulence Program at NCAR provides NCAR staff, visitors and outside collaborators with the tools and advice necessary to do direct simulation of geophysical turbulence. Initially funded in part by the Army Research Office, the program has been successful and is continuing. R. Kerr, who was funded by this ARO grant, is staying on at NCAR on an AFOSR grant.

Kerr's major contribution during this period was the development of a community turbulence model that would make available to the meteorological community some of the recent developments in turbulence simulation. The objective was to make a variety of spectral techniques, the most powerful numerical methods for studying turbulence, available in a single package that would include data management, graphics, and analysis. There are currently three university groups using this code as well as five users at NCAR. Topics that have been covered include fundamental turbulence, convection, convection with mean wind shear, stratified turbulence, and compressible turbulence. In addition to supporting Kerr, this ARO program also funded one month of Jeff Weil's research on Lagrangian stochastic modeling. A synopsis of his research is also included here.

The community turbulence code currently has two ways of solving the Poisson equation and satisfying boundary conditions. One part uses Fourier series (sines or cosines in all three directions) and has been used for the fundamental turbulence studies discussed below. The other part uses Chebyshev polynomials in the vertical direction to provide extra resolution near walls. The goal in using Chebyshev polynomials is to use the mesh refinement along with a sophisticated pressure elimination scheme to simulate no-slip boundary layers at moderate turbulent Reynolds numbers. By simulating all scales we hope to resolve small-scale shear instabilities that might have large-scale effects. Furthermore, if we can reach the beginning of the high Reynolds number scaling regime applicable to the atmosphere, then these simulations can be used to predict atmospheric scaling laws that have eluded earlier modeling efforts. Modelers can use such codes to run "experiments" that can be used for comparison when atmospheric or laboratory experiments are not available.

Kerr's initial research consisted of finishing several publications based on calculations done with an early version of this model. These publications are:

Kerr, R. M., 1987: Histograms of helicity and strain in numerical turbulence. *Phys. Rev. Let.*, **59**, 783.

Ashurst, W. T., A. R. Kerstein, R. M. Kerr, & C. H. Gibson, 1987: Alignment of vorticity and scalar gradient with strain rate in simulated Navier–Stokes turbulence. *Phys. Fluids*, **30**, 2343.

Gibson, C. H., & R. M. Kerr, 1988: Evidence of turbulent mixing by the rate–of–strain. Submitted to *Phys. Fluids*.

R.M. Kerr, 1990: Velocity, scalar, and transfer spectra in numerical turbulence. *J. Fluid Mech.*, **211**, 309.

2. NUMERICAL INVESTIGATIONS AND PARTICIPANTS

2.1. *Vortex Reconnection — Incompressible Flow*

The first major new calculation Kerr did with the code was vortex reconnection. It had been suggested that vortex reconnection might provide a means of inducing the turbulent cascade. In collaboration with F. Hussain from the University of Houston, Kerr showed that vortex reconnection provides a mechanism for producing vortex sheets and has trends consistent with the existence of a singularity of the Euler equations. The question of whether the incompressible, three-dimensional Euler equations have a singularity—whether in the limit of zero viscosity the vortex sheets will merge—has been one of the most important questions in theoretical fluid mechanics. Neither analytical methods nor modeling have been able to give a convincing answer to this question. Our calculation showed that some of the assumptions used in models that did find a singularity were incorrect and showed that all earlier direct calculations lacked sufficient resolution to determine whether there is a singularity. These results were presented in 1988 in a poster session at a meeting on Advances in Fluid Turbulence in Los Alamos, in an invited lecture at an Applied Mechanics and Engineering Sciences Conference in Berkeley by Kerr, and at the IUTAM meeting in Grenoble by Hussain. The reference is:

Kerr, R. M., & Hussain, F., 1989: Simulation of vortex reconnection. *Physica D*, **37**, 474.

2.2. *Vortex Reconnection — Compressible Flow*

It has been theorized by Hussain that vortex reconnection could be a source of turbulent acoustic noise. In order to study this, a graduate assistantship for Davinder Virk from the University of Houston was granted. Virk has added compressibility to the code and has extended the calculations of vortex reconnection done by Kerr and Hussain into the compressible regime. Distinct differences with the incompressible calculations are seen, but the calculations have not yet been completed. Initial results will appear in the proceedings of the IUTAM meeting on Topological Fluid Mechanics held in Cambridge, England. Kerr's expenses to this meeting were provided by the conference organizers and he presented an invited lecture. The reference is:

Kerr, R. M., Virk, D. & F. Hussain, 1989: Effects of incompressible and compressible vortex reconnection. To appear in proceedings of IUTAM meeting on Topological Fluid Dynamics, Cambridge University and submitted to *Phys. Fluids.*

2.3. *Convection*

Wanshu Wu, a student at the University of Oklahoma, visited NCAR as an NCAR graduate assistant for periods in 1987, 1988 and 1989. She helped debug the boundary layer algorithms and used them to study sheared convection. Initial low Rayleigh number simulations showed that significant helicity can be generated in a convectively driven boundary layer and can suppress the non-linear terms of the Navier-Stokes equations. This would support Lilly's ideas concerning the importance of helicity in supercell storm generation. Later, higher Rayleigh number simulations showed that the mechanism broke down when the flow became more turbulent. She has returned to the University of Oklahoma to finish her PhD.

Wu also began some simulations of low-aspect-ratio convection. Kerr has continued these calculations and has now done both small and large aspect ratio Rayleigh-Bénard calculations with the Rayleigh number as large as 5×10^7. The highest Rayleigh number achieved with earlier calculations was 5×10^5. The largest aspect ratio is 6 in each horizontal direction to 1 in the vertical and the largest calculation to date required $288 \times 288 \times 96$ mesh points and would need several hundred Cray-XMP hours to get statistically steady results. Since these resources are not available, the largest calculation done with adequate statistics was at Ra=10^7 on a 192 $\times$ 192 $\times$ 64 mesh. While these Rayleigh numbers are significantly less than atmospheric Rayleigh numbers, they are close to the maximum Rayleigh number achieved in laboratory experiments using water and should be in the Reynolds number similarity regime characteristic of the atmosphere. For example, at this Rayleigh number there is a distinct Kolmogorov inertial subrange and Priestley's scaling laws, which have been found to be applicable to the atmospheric boundary layer, are found. One objective of this project was to find the "hard" turbulence regime identified in low-aspect-ratio experiments at the University of Chicago up to Ra=10^{12} where Priestley's laws are not obeyed. Initial results suggest that "hard" turbulence is an artifact of the low-aspect ratio used in the experiments and is not directly applicable to atmospheric convection.

Two new post-doctoral associates at NCAR using this code are O. Thual and M.P. LeLong. Thual plans to study low Prandtl number convection with applications towards stellar atmospheres and coolants in breeder reactors. LeLong is studying gravity wave propagation in stratified flow. James Hill and his students at Iowa State have been continuing to use the community turbulence model for studying chemical reactions.

2.4. *Numerical and Analytical Calculations of Non-Gaussian Statistics*

In another approach to understanding the small scales, J. Herring at NCAR in collaboration with Kerr and R. Kraichnan and H. Chen from Los Alamos, has compared various statistics pertaining to the distribution function of turbulence from numerical simulations to predictions of an analytic theory of turbulence. Herring has presented these results at an invited lecture at a meeting of the International Union of Theoretical and Applied Mechanics in Grenoble, France. The reference is:

Chen, H., J. R. Herring, R. M. Kerr, & R. Kraichnan, 1989: Non-Gaussian statistics in isotropic turbulence. *Phys. Fluids A*, **1**, 1844.

2.5. *Stably Stratified Shear Flow*

One of the objectives of this program was to study stably stratified shear flow. T. Horst initially came to NCAR from Battelle Northwest to study this problem using the boundary-layer algorithms in the community turbulence model. So far only some low Reynolds number flows have been simulated where the amount of stratification necessary to suppress the turbulence is so small that the results are considered insignificant. To see interesting effects we now believe that much higher Reynolds numbers must be simulated. For adiabatic shear flow the ability of codes like this to reach such Reynolds numbers was demonstrated over 10 years ago, but significantly greater resolution and computational expense that is not available to this program is needed to reach this regime. Additional stratified shear flow calculations have been postponed until this issue can be resolved. Kerr has recently found a simple modification to the advection algorithm that makes it possible to reach the necessary turbulent regime on coarse meshes. This should make it possible to do a large number of test calculations cheaply before doing a fully resolved, expensive calculation. Horst will be staying at NCAR in the Atmospheric Technology Division and continuing some of these simulations.

3. LAGRANGIAN STOCHASTIC MODELING

Weil (1990) used a Lagrangian stochastic model of particle trajectories to diagnose the asymmetry in bottom-up and top-down diffusion in the convective boundary layer (CBL), a phenomenon found in the large-eddy simulations by Moeng and Wyngaard (1984; 1989). The analysis was simplified by considering the diffusion properties of hypothetical boundary layers with vertical velocity variance (σ_w^2) and third-moment ($\overline{w^3}$) profiles qualitatively similar to those in the CBL but with a uniform velocity time scale, τ. The concentration field, $C(z)$, due to a uniform area source was found by superposing the fields due to (crosswind) line sources distributed in the along-wind direction.

For inhomogeneous Gaussian turbulence, an asymmetry in diffusion patterns about the midplane of the boundary layer resulted from the vertical asymmetry in $\sigma_w(z)$. For small τ's, this was predictable from an eddy-diffusion model since the effective diffusivities (K) from the simulations approached the long-time limit of Taylor's (1921) theory, $K = \sigma_w^2\tau$. However, for sufficiently large τ's, K theory was inapplicable since $\partial C/\partial z$ exhibited sign changes and K had singularities, indicating regions of a countergradient flux. The causes of the K model breakdown were the memory (large τ) and inhomogeneity of the turbulence, which were measured through the dimensionless parameter $\tau\partial\sigma_w/\partial z$. Simulations with skewed turbulence showed that a positive skewness led to an asymmetry between bottom and top sources in both $\partial C/\partial z$ and K regardless of the form of the variance profile—whether it was symmetric about the midplane of the boundary layer or not. This asymmetry was caused by the bias in the vertical velocity

probability density function.

Moeng, C.-H., and J. C. Wyngaard, 1984: Statistics of conservative scalars in the convective boundary layer. *J. Atmos. Sci.*, **41**, 3161–3169.

Moeng, C.-H., and J. C. Wyngaard, 1989: Evaluation of turbuent transport and dissipation closures in second-order modeling. *J. Atmos. Sci.*, **46**, 2311–2330.

Taylor, G. I., 1921: Diffusion by continuous movements. *Proc. London Math. Soc.*, **20**, 196–211.

Weil, J. C., 1990: A diagnosis of the asymmetry in top-down and bottom-up diffusion using a Lagrangian stochastic model. *J. Atmos. Sci.*, **47**, 501–515.